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Very Big Accelerators as Energy Producers

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One consequence of the application of superconductivity to accelerator construction is that the power consumption of accelerators will become much smaller. This raises the old possibility of using high energy protons to make neutrons which are then absorbed by fertile uranium or thorium to make a fissionable material like plutonium that can be burned in a nuclear reactor [1]. The Energy Doubler/Saver being constructed at Fermilab is to be a superconducting accelerator that will produce 1000 GeV protons. The expected intensity of about 10^{12} protons per second corresponds to a beam power of about 0.2 MW. The total power requirements of the Doubler will be about 20 MW of which the injector complex will use approximately 13 MW, and the refrigeration of the superconducting magnets will use about 7 MW. Thus the beam power as projected is only a few orders of magnitude less than the accele ator power. But each 1000 GeV proton will produce about 60,000 neutrons in each nuclear cascade shower that is releaseq in a block of uranium, and then most of these neutrons will be absorbed to produce 60,000 plutonium a toms. Each of these when burned will Subsequently release about 0.2 GeV of fission energy to make a total energy of 12,000 GeV (20 ergs) for each 1000 GeV proton. Inasmuch as megawatts are involved, it appears to be worthwhile to consider the cost of making the protons to see if there could be an overall energy production.

A high energy proton accelerator seems at first glance to be an unlikely device for producing energy in this manner but high energy does have a few special advantages. One is that once the protons have been injected and accepted by the accelerator at the low energy of injection, then the subsequent losses during the acceleration to high energy are essentially zero. Another is that space charge limitations of intensity become less important at high energy. A third advantage is that the betatron oscillations of the beam are damped as the energy increases. This means that the emittance of the beam gets better as the energy grows and hence the beam can be transferred to rings of smaller aperture (lower refrigeration costs) as the energy and hence ring size increases. This assumes that the accelerator consists of a series of magnet rings of ever increasing radius. Alternatively, more protons can be injected into a given aperture and accelerated. The main point is that the number of neutrons produced is roughly proportional to the beam power and this can be made large by increasing both the intensity *and* the energy of the protons. The intensity of an accelerator usually runs into a hard limit imposed by space charge and resonance phenomenon, but the energy can be increased without limit.

A disadvantage of very high proton energy is that the relative number of neutrons produced in the nuclear shower gets somewhat less as the energy of the initial proton increases because the fraction of the electromagnetic component increases with energy. This adverse effect could be vitiated in part by accelerating deuterons (or particles of even higher mass) so that the energy per nucleon is lower. In any case, once a proton has gone through the expensive and inefficient business of being produced and accelerated to about 10 GeV energy, then all the energy possible should be pumped into it during the efficient part of the acceleration process that brings it to high energy.

Now let us consider the process a little more quantitatively. We assume that the number of neutrons produced in a nuclear shower in U^{238} when N protons of energy E are incident is proportional to the energy in the shower, i.e., to aNE, where the constant a will have a value of roughly 60 neutrons per GeV, about half of which come from fission of U^{238} Then the potential power P produced overall when these neutrons are nearly all absorbed to form plutonium is given by

$$P = 0.2aNE - P_0 - bNE,$$

where 0.2 is the energy per fission in GeV, P_0 is the power required to run the accelerator when no protons are accelerated, and bNE is the power used by the RF system to accelerate the protons. The constant b is a measure of the inefficiency of producing RF power from the electrical mains; it has a value of roughly 2 although this might be improved to a value of about 1.5.

For a given accelerator, if $0.2a$ is greater than b, as it is for the Energy Doubler, then there will be a proton intensity N_0 above which more power will be available from the plutonium burned than will be used by the accelerator. This value is given by

$$N_0 \approx P_0/10E.$$

For the Energy Doubler at Fermilab plus all its injector stages, P_0 will be roughly 20 MW, and N_0 then comes out to be about 2×10^{13} protons per second. This is about twenty times the expected intensity - but it is far from being

unattainable. An intensity of 10^{13} protons per second will make about 15 Megawatts of fission energy available; this does not count the energy put into the accelerator. For an overall production of 15 MW, an intensity of 3×10^{13} protons would be required; or more generally

$$P \approx 10(N - N_0)E.$$

Now the above calculations are pessimistic in that they assume that the beam energy is thrown away. Furthermore there will be considerable fission energy produced by fast neutrons being absorbed in the U^{238} during the course of the cascade shower. Let us now assume that both of these forms of energy are available for use. Mr. Andreas VanGinneken has made a rough computer calculation following the shower development and assuming that each U^{238} fission leads to 3 Pu^{239} nuclei, but that the Pu^{239} fission is not used as a source of neutrons. His results are tabulated in Table I and illustrate the relative increase of the electromagnetic component with energy. Remaking the calculations for the rougher break-even intensity made above, we find N_0 to be close to 10^{13} protons per second, an intensity which might be attainable even in the Doubler by increasing the rate of pulsing, or by resorting to a stacking process, or by adding a second ring of superconducting magnets. He has also made the same calculation at 100 and 300 GeV.

It appears then that an accelerator that is similar to the Energy Doubler could be made to be energy productive. Starting from the beginning, perhaps the injector system could be made to use less ertergy and produce higher intensities. One could also optimize the size of the rings so as to reduce the refrigeration requirement and to raise the intensity capability. An important improvement (and one assumed in all the above) would be to make at least two magnet-rings back-to-back so that the electric energy could oscillate from one to the other rather than just being put back into the power mains. This would double the intensity and would make efficient use of the injection system, for one ring could be loaded while the other was accelerating the protons previously loaded into it. My guess is that the optimum energy of the accelerator will be smaller, but this will depend on details of the injection system and on the shape of the real estate that is available. Values of N_0 for other energies are given in Table I: they vary roughly inversely with the energy but 100 GeV gives fractionally about 30% more energy per proton than does 1000 GeV.

Capital costs, of course, are equally significant. The bare-bones accelerator might cost, as a very rough guess, about $200 million for a plant that would produce the fuel to power a 100 MW fission plant. A larger installation might of course cost relatively less per MW.

When the kind of intense proton beam considered above is to be absorbed on a target, a serious problem arises. Even with our present intensities at 400 BeV, i.e., about 10^{12} protons/sec, targets tend to disappear. One can imagine that the target might be a slurry of uranium oxide and heavy water. Each pulse of protons will last about twenty microseconds, then the water will turn to stearn and start to explode. This could move a piston in the classical manner until the stearn has cooled (or has passed to a next stage) and has been replaced again by the slurry. Such a dramatic device need not be used; rather the stearn could be taken off in the more usual manner of any power reactor and then used for the generation of energy.

If undepleted uranium were to be used (or were slightly enriched with Pu) then a magnification of the neutrons would occur, but still without having a supercritical reactor. This might bring the break-even intensity of protons needed for power production down by another factor of ten, which would then put it within range of the present Energy Doubler accelerator at Fermilab.

There are probably better ways of producing plutonium, but it does appear that it would be feasible to construct an intense proton accelerator that would produce more energy than it consumes. A further more careful study of the accelerator as well as of the plutonium production in the cascade showers would determine the optimum proton energy for such a device. One happy result of all that intensity would be that a truly magnificent neutrino source could be produced!

I wish to thank Mr. A. Van Ginneken for making the nuclear shower calculation.

Table I
Calculation of A. VanGinneken for protons on
a large U^{238} beam dump

	100 Gev	300 Gev	1000 Gev
Ioniz. of Hadron Shower*	.34	.29	.23
E. M. Showers*	.32	.40	.48
U^{238} Fission*	2.2	1.9	1.6
Pu^{239} Fission*	13.8	11.8	10.2
Total*	16.6	14.3	12.5
N^0	8.6×10^{13}	3.4×10^{13}	1.2×10^{13}
(Pu nuclei)/proton	7000	18,000	62,000
Total Energy/1013 protons	2.7	6.9	20 MW

* Fraction of incident energy recovered: calculations assume that each U238 fission makes three Pu239 nuclei. The fission of Pu239 has not been considered as a source of neutrons.

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[1] Shades of E. O. Lawrence's MTA project! See *Atomic Shield*, page 425, by R. Hewlett and F. Duncan. I have also learned that there is a project in Canada to use an accelerator this way. See W. Metz, Science, July 23, 1976, Page 307.